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Power Measurements to Excavate Lunar Soil Simulant GRC-3B Using Arc Backhoe Trajectories

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In-Situ Resource Utilization (ISRU) project objectives:

- Measure fundamental forces to excavate granular soils that may be on the Moon and Mars.
 - Various quantities
 - Both loose and compacted
- Validate existing excavation analytical model algorithms with data.
- Use model to guide excavator designs for various soil conditions.

Power measurements were also taken.

Scope of this paper:

- Test apparatus
- Test procedures
- Power measurements in lightly compacted and compacted GRC-3B
- Conclusions

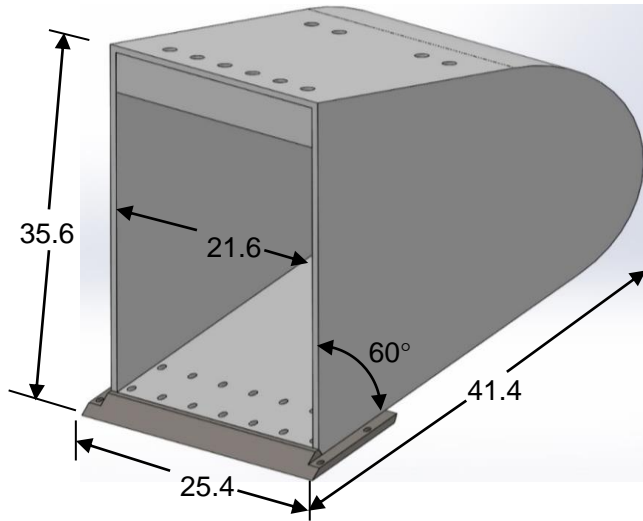
Test Apparatus

Excavation Lab at NASA Glenn Research Center houses the Advanced Planetary Excavator (APEX) and soil bins inside a dust enclosure.

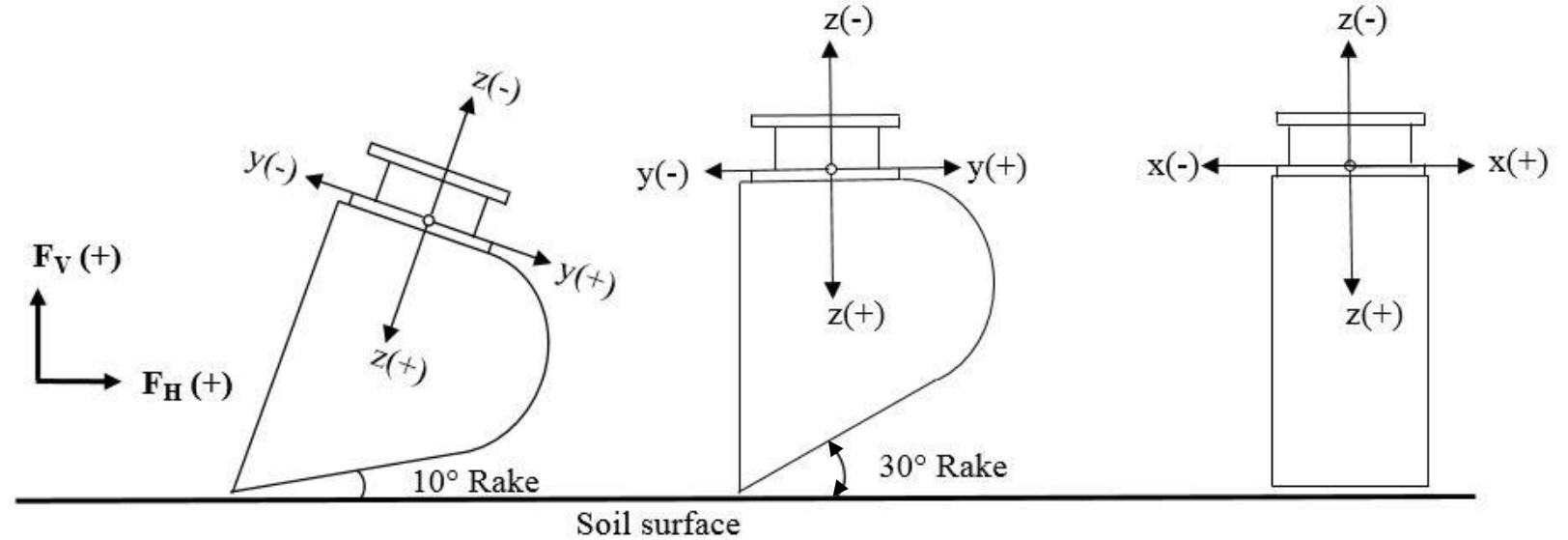
- APEX uses a 6-axis load cell between wrist plate and bucket to measure forces
- Aluminum bucket with 30° single bevel steel cutting edge
- Soil bin: 76 wide by 183 long by 76 high (cm)
- Shaker table used for soil compaction
- Cone penetrometer to assess soil condition
- Platform scale: 0.61-m square, 0 to 2224 N range, 0.22 N resolution
- Digital power meter recorded current, DC voltage, and total power to the APEX



Load cell origin and force measurement axes



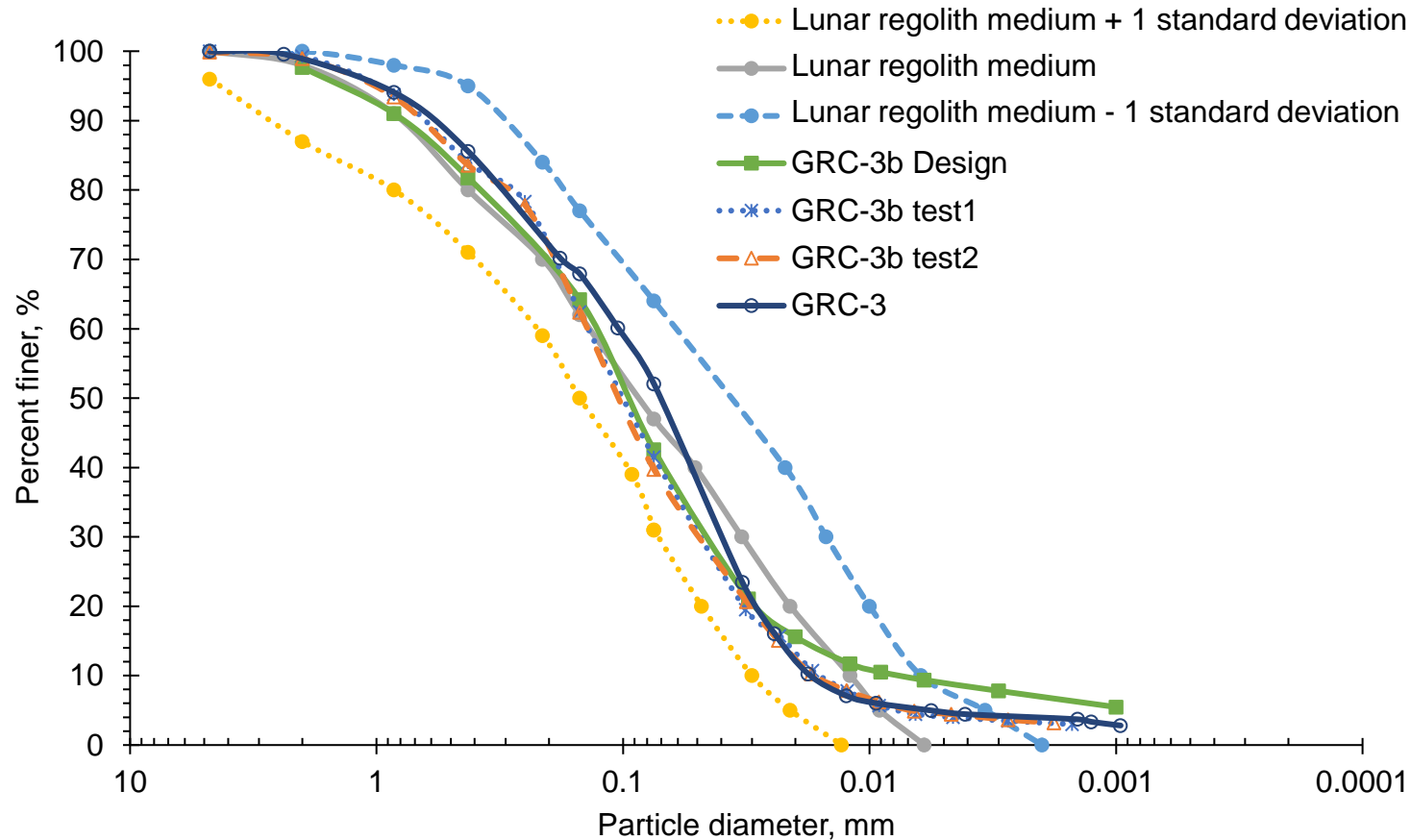
Bucket dimensions in cm.
Bucket volume = 15600 cm³



Range: 1334 N in x, y; 3892 N in z

Uncertainty: +/- 16.7 N in x, y; +/- 29.2 N in z

GRC-3B particle size distribution compared to lunar regolith



Test Procedures

Soil preparation:

1. Loosen with auger
2. Level
3. Compact, if needed, using shaker table at 60 Hz for 4 minutes.*
4. Record soil strength
 - Cone penetrometer
 - Eight test locations—four on either side of bucket path

*Compacted soil surface is slightly undulated.

Rough estimate of bulk density:

Lightly compacted: 1540 kg/m^3

Compacted: 1750 kg/m^3

Test Procedures—Trajectories

- Conduct in air to establish load cell tare
- Conduct in GRC-3B and subtract tare

Trajectories are planned and repeatable.

Backhoe Arc Trajectories

- Shoulder and elbow joints fixed to achieve the rake angle at the target depth
- APEX arm with bucket rotated about the elbow pivot
- Starts and stops with bucket blade tip 2.54 cm above soil
- Stopped at target depth for photos, then resumed

Tests Conducted

Trajectory	Soil condition	Rake angle, °	Depth, cm
Backhoe	Lightly compacted	10	10
		20	
		30	
		10	20
		20	
		30	
Backhoe	Compacted	10	5
		20	
		30	
		10	10
		20	
		30	
Backhoe	Compacted	10	20*

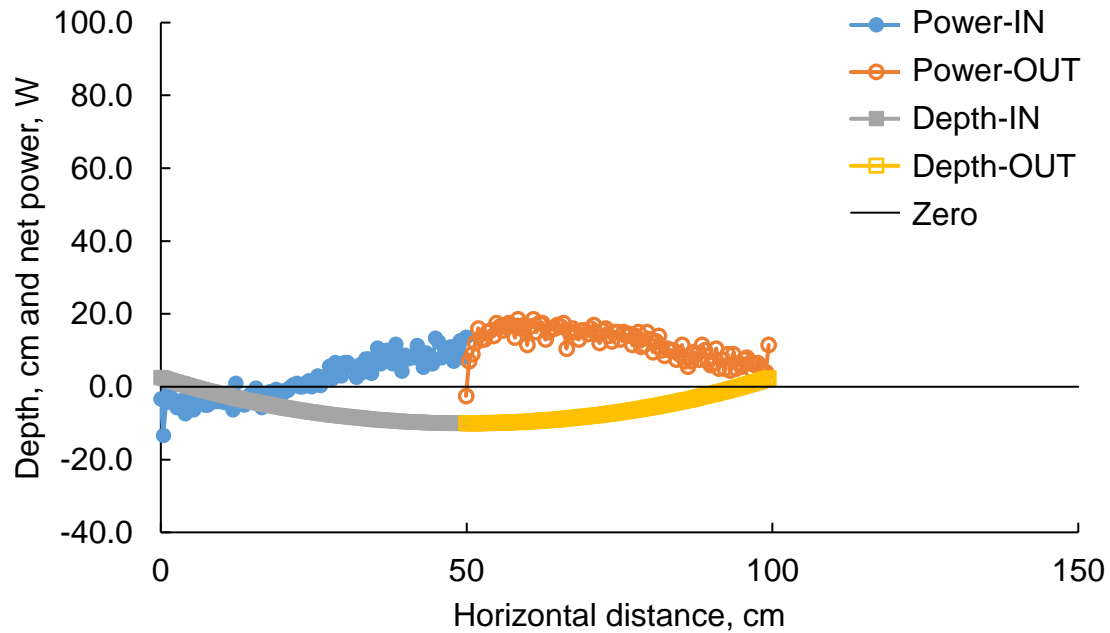
*Load cell range was exceeded.

For 10° and 20° rake, target depth occurred directly under elbow joint and is maximum depth.

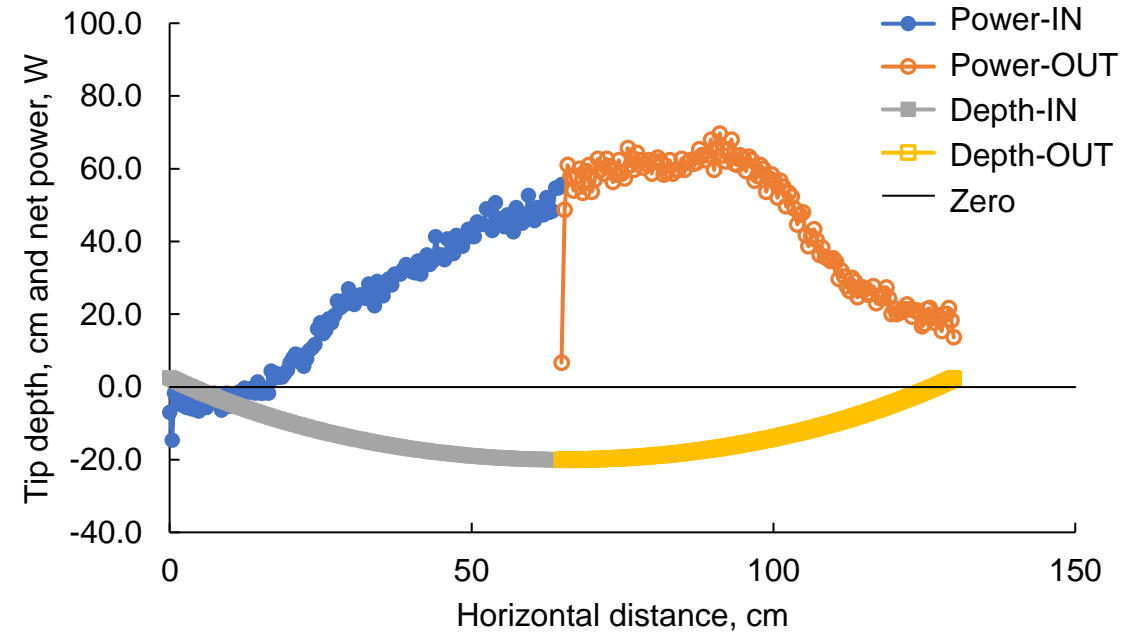
Summary of maximum net power for backhoe arc trajectories

Rake (°)	Depth (cm)	Maximum net power in lightly compacted GRC-3B (W)	Maximum net power in compacted GRC-3B (W)
10	5	---	16.3
20	5	---	23.6
30	5	---	52.3
10	10	18.5	48.3
20	10	18.2	50.7
30	10	40	87.7
10	20	69.7	269.3
20	20	80	---
30	20	172.7	---

Net power and tip depth of backhoe trajectory in lightly compacted GRC-3B

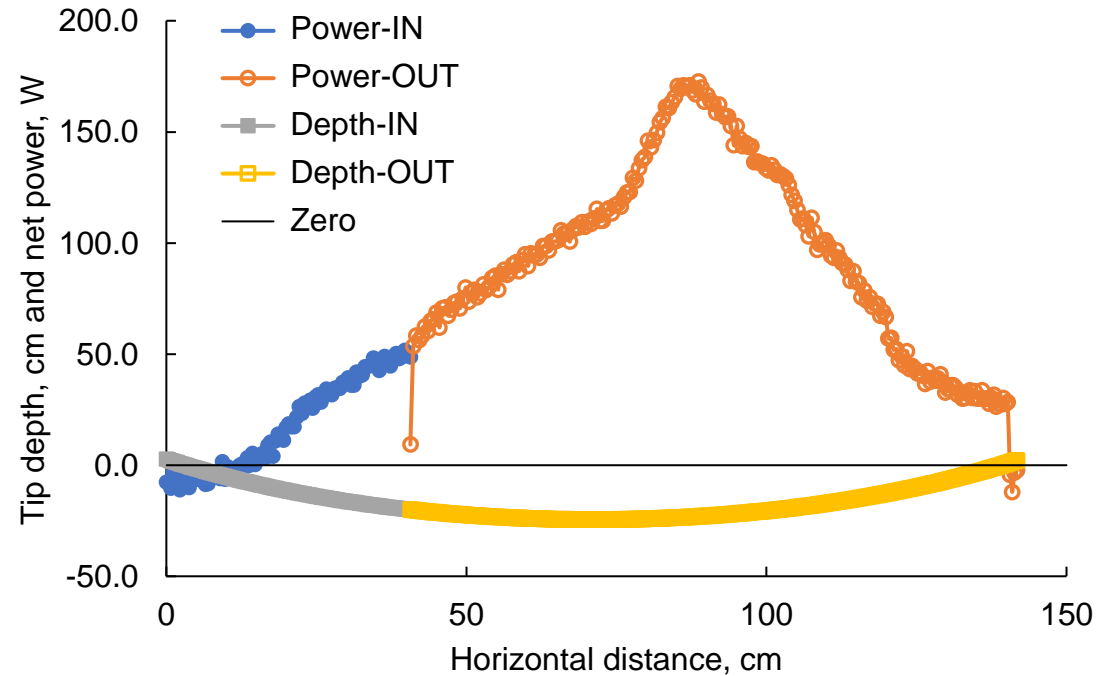


5 cm/s, 10° rake angle at 10-cm depth



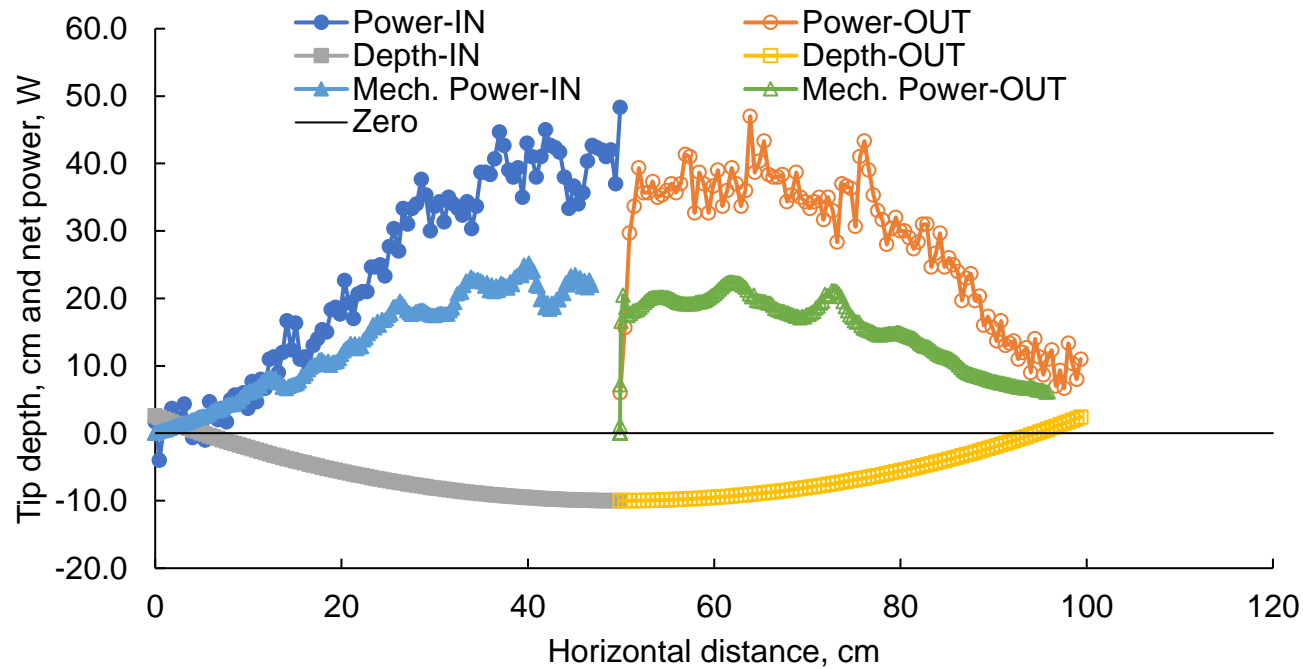
5 cm/s, 10° rake angle at 20-cm depth

Net power and tip depth of backhoe trajectory in lightly compacted GRC-3B 5 cm/s, 30° rake angle at 20-cm depth



- Maximum depth was 24.5 cm at which rake angle was 13.4°.
- Target rake angle and depth could not be reached directly under the elbow joint.

Net power, mechanical power, and tip depth of backhoe trajectory in compacted GRC-3B 5 cm/s, 10° rake angle at 10-cm depth



Summary of results in lightly compacted GRC-3B

Rake (°)	Depth (cm)	Distance between tip entry and exit (cm)	Trajectory to bucket volume ratio (%)	Time (s)	Mass dug (kg)	Net energy (W-s)	Net energy per mass dug (W-s/kg)	Mass/ time (kg/s)
10	10	89	83	20.7	11.59	142.2	12.27	0.56
20	10	91	85	21.0	9.21	142.6	15.48	0.44
30 (11.7)	10 (15.4)	110	159	24.9	21.05 ¹	512.3	24.34	0.85
10	20	123	232	28.0	27.71	934.9	33.74	0.99
20	20	125.6	236	28.5	26.38 ²	1022.3	38.75	0.93
30 (13.4)	20 (24.5)	135.7	315	31.0	29.21 ³	2139.2	73.24	0.94

¹Max. depth of swing out was 15.4 cm. ²Bucket over full. ³Some spillage. Max. depth on swing out was 24.5 cm.

Summary of results in compacted GRC-3B

Rake (°)	Depth (cm)	Distance between tip entry and exit (cm)	Trajectory to bucket volume ratio (%)	Time (s)	Mass dug (kg)	Net energy (W-s)	Net energy per mass dug (W-s/kg)	Mass/ time (kg/s)
10	5	64	30	16.1	6.96	134.7	19.78	0.43
20	5	65	30	16.3	5.85	186.8	31.93	0.36
30 (12.2)	5 (10.1)	90.1	85	20.9	18.69 ¹	542.8	29.04	0.89
10	10	89.6	83	20.6	19.00	532.6	28.03	0.92
20	10	91	85	21	15.22	584.9	38.43	0.72
30 (13)	10 (14.6)	117.7	161	24.5	26.78 ²	1088.0	40.63	1.09
10	20	123.5	233	28.1		3240.5		

¹Max. depth on swing out was 10.1 cm. ²Max. depth on swing out was 14.6 cm.

Summary and Conclusions

- The maximum net power for the backhoe trajectories tested in lightly compacted GRC-3B ranged from 18 to 173 W and in compacted GRC-3B, ranged from 16 to 269 W.
- The net energy for the backhoe trajectories ranged from 135 to 3240 W-s.
- The energy per mass GRC-3B dug with backhoe trajectories ranged from 12.3 to 73.2 W-s/kg in lightly compacted conditions and from 19.8 to 40.6 W-s/kg in compacted conditions.
- The rate of mass excavated ranged from 0.36 to 1.09 kg/s. These values do not include lifting the bucket up out of the soil.
- Soil condition, dig depth, rake angle, and trajectory to bucket volume ratio all affect the net power and energy needed to excavate lunar regolith and the rate at which it can be acquired.
- The mechanical power, the power consumed by interaction of the bucket with the soil, approached 50 to 60 percent of the net wall power in compacted soil as trajectory depth and forces increased.

Summary and Conclusions (Concluded)

- Power requirements need to account for inefficiencies converting electrical power to mechanical power and could be approximately double the mechanical power due to tool interaction with the soil.
- The power measurements provided here for excavating in granular lunar soil simulant, GRC-3B, can provide some insight and guidance to mission planners in developing power requirements for lunar excavation and to designers in developing energy-efficient excavation tools and processes.
- Efforts to correlate properties and behavior of GRC-3B in ambient Earth environment to those of lunar regolith in vacuum conditions are recommended as well as additional excavation tests for long-term repeatability.
- The APEX and the Excavation Lab provide a capability to evaluate the effectiveness, efficiency, and power requirements for various digging tools.